

Transient Phenomena in Anomalous X-ray Pulsars

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Abstract. In 2003 a previously unpulsed Einstein and ROSAT source cataloged as soft and dim (L_X of few $\times 10^{33}$ erg s $^{-1}$) thermal emitting object, namely XTE J1810-197, was identified as the first unambiguous transient Anomalous X-ray Pulsar. Two years later this source was also found to be a bright highly polarized transient radio pulsar, a unique property among both AXPs and radio pulsars. In September 2006 *Swift* Burst Alert Telescope (BAT) detected an intense burst from the candidate AXP CXOU J164710.2–455216, which entered in an outburst state reaching a peak emission of at least a factor of 300 higher than quiescence. Here, we briefly outline the recent results concerning the outburst phenomena observed in these two AXPs. In particular, XTE J1810-197 has proved to be a unique laboratory to monitor the timing and spectral properties of a cooling/fading AXP, while new important information have been inferred from X-ray and radio band simultaneous observations. CXOU J164710.2–455216 has been monitored in X-rays and radio bands since the very beginning of its outbursting state allowing us to cover the first phases of the outburst and to study the timing and spectral behavior during the first months.

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INTRODUCTION

At the beginning of the X-ray astronomy era the study of the X-ray variability (both of the flux and timing properties) of Cen X-3 allowed astronomers to unambiguously assess the binary nature of the source and to identify the accretion of mass, flowing from the companion onto a rotating neutron star, as the main mechanism to produce X-rays [1, 2]. Since then, several classes of high energy sources hosting a compact object have been identified and their variability, observed on different timescales, used to test models and/or to study the emission mechanisms as a function of flux (while keeping fixed other parameters, such as the distance and the geometry of the system). For the class of accreting neutron stars this approach was successful in confirming, among others, the presence of a centrifugal barrier to accretion, testing the dependence of the period derivative with respect to the source luminosity, and studying the change in the photon propagation direction as a function of the accretion rate by means of the pulse shape changes [fan and pencil beam model; as an example see 3, 4, 5]. Isolated neutron stars are relatively constant sources, making the above approach unreliable. However, there are two small classes of isolated neutron stars which show spectacular events during which their luminosity may change up to 10 orders of magnitude on timescales down to few mil-

liseconds. These objects are better known as Anomalous X-ray Pulsars (AXPs; 10 objects plus 1 candidate) and Soft γ -ray Repeaters [SGRs; 4 objects plus 2 candidates; for a review see 6]. It is believed that AXPs and SGRs are linked at some level, owing to their similar timing properties (spin periods in the 2-12 s range and period derivatives \dot{P} in the 10^{-13} – 10^{-11} s s $^{-1}$ range). Both classes have been proposed to host neutron stars whose emission is powered by the decay of their extremely strong magnetic fields [$> 10^{15}$ G; 7, 8].

Different types of X-ray flux variability have been displayed by AXPs. From slow and moderate flux changes (up to a factor of few) on timescales of years (virtually all the object of the class), to moderate-intense outbursts (flux variations of a factor up to 10) lasting for 1-3 years (1E 2259+586, and 1E 1048.1–5937), to dramatic and intense SGR-like burst activity (fluence of 10^{36} – 10^{37} ergs) on sub-second timescales [4U 0142+614, XTE J1810-197, 1E 2259+586 and 1E 1048.1–5937; see 9, for a review on the X-ray variability]. The first notable recorded case of flux variability was the 2002 bursting/outbursting event detected from 1E 2259+586, the only known event in which a factor of ~ 10 persistent flux enhancement in an AXP was followed (or preceded) by the onset of a bursting activity phase during which the source displayed more than 80 short bursts [10, 11]. The timing and spectral properties of the sources changed sig-

nificantly and recovered the pre-bursting activity phase values within few days, likely due to the relatively high luminosity DC level ($\sim 10^{35} \text{ erg s}^{-1}$). However, it was only in 2003 that the first transient AXP was discovered, namely XTE J1810-197, which displayed a factor of >100 persistent flux enhancement with respect to the unpulsed pre-outburst quiescent luminosity level [$\sim 10^{33} \text{ erg s}^{-1}$; 12, 13, 14, 15]. Unfortunately, the initial phases of the outburst were missed and we do not know whether a bursting activity phase, similar to that of 1E 2259+586, occurred also for this source, though four bursts have been detected by RossiXTE between 2003 September and 2004 April and unambiguously associated with XTE J1810-197 [16]. In 2006 the candidate AXP CXOU J164710.2–455216 displayed a bursting-outbursting behavior with a maximum flux variability of > 300 , followed by extreme and daily changes both in the spectral and timing properties [17, 18, 19].

These two sources currently represent our best opportunity in order to study the evolution of the main spectral and timing parameters as a function of flux by keeping fixed other parameters (such as distance and geometrical angles) otherwise difficult to infer (similarly to the pioneering studies on accreting X-ray pulsars). In the following pages we will briefly outline (i) the recent results obtained from the analysis of the latest 4 years *XMM-Newton* monitoring observations of XTE J1810-197 as it approached to quiescence, (ii) the comparison of X-ray and radio emission from XTE J1810-197 by means of two $\sim 8\text{hr}$ -long simultaneous campaigns with *XMM-Newton* and Parkes, (iii) and the results of the first 6 months monitoring of CXOU J164710.2–455216 during the first phases of its current outburst by means of *Swift*, *Chandra* and *XMM-Newton* in the X-rays and Parkes in the radio band.

XTE J1810–197: FROM OUTBURST TO QUIESCENCE

Since the very first *XMM-Newton* 2003 observations of XTE J1810-197, carried out approximately one year after the onset of the outburst, it was evident [13] that the source spectral shape (two blackbodies with $kT=0.29\pm0.03 \text{ keV}$ and $R_{BB}\approx 5.5 \text{ km}$, and $kT=0.70\pm0.02 \text{ keV}$ and $R_{BB}\approx 1.5 \text{ km}$; $L_X\sim 5\times 10^{34} \text{ erg s}^{-1}$ in the 0.5-10 keV range) was significantly different from that serendipitously recorded by ROSAT in 1992 (one BB with $kT\approx 160 \text{ eV}$ and $R_{BB}\approx 10 \text{ km}$; extrapolated luminosity in the 0.5-10 keV range of $L_X\sim 7\times 10^{32} \text{ erg s}^{-1}$ and for a distance of 3.3 kpc). Moreover, the source showed a 5.54 s pulsation with a pulsed fraction of nearly 45% during outburst, while an upper limit of 24% was inferred from the

ROSAT data. The above issues originated a number of important questions awaiting for an answer: Is the soft BB component detected by *XMM-Newton* evolving into the quiescent BB component seen by ROSAT? Alternatively, is the emission from the whole surface always present? What happens to the higher temperature BB component as the source approaches to quiescence? Which is the pulsed fraction level of the source in quiescence (if detectable)? Does the outburst changed permanently the timing/spectral properties (such as the pulsed fraction, the flux and temperature or size of the quiescent BB component) of the source?

In order to try answering to the above questions we reduced all the archival (6) and still proprietary (2) *XMM-Newton* observations [for the details see 20, 21] and fitted the eight spectra all together. All the spectra have been rebinned in order to ensure that each background-subtracted spectral channel has at least 25 counts, and that the instrumental energy resolution is not oversampled by a factor larger than 3 [22, ; indeed the correct application of the above rules prevents artificially low (good) reduced χ^2 s.]. In particular, we can outline the obtained results as follows:

2BB model: By extending the spectral recipe outlined by [13, 23] we applied the two BB spectral fit analysis to the fading phases of XTE J1810-197 until March 2007 when the flux source was ~ 1.2 times above the pre-outburst level (reduced $\chi^2\sim 1.23$ for 975 degree of freedom, d.o.f.; $N_H=0.58\pm 0.02\times 10^{22} \text{ cm}^{-2}$). While the soft BB component smoothly approaches to that in quiescence (see Figure 1, left panel, 2nd and 3rd plots), we note a number of ambiguities difficult to account for by means of simple assumptions. The hard component BB radius is not monotone and it increases after 2.5 years of smooth decrease (left panel, 4th plot) while the temperature approaches to that of the soft BB in 2003 (left panel, 5th plot). Moreover, none of the spectral parameters or components is able to account for the flattening, at the 25% level, showed by the pulsed fraction evolution (left panel, 1st plot) [21].

3BB model: The addition of a further BB component gives a better fit (reduced $\chi^2\sim 1.15$ for 973 d.o.f.; $N_H=0.70\pm 0.02\times 10^{22} \text{ cm}^{-2}$; F-test probability gives 7.3σ) though not yet satisfactory. Notably, the fit gives parameters and flux (for the coldest BB) which are virtually equal to those inferred in quiescence. Even more interesting, the hottest BB components show a nearly constant evolution of the temperatures (see Figure 1, right panel, 3rd and 5th plots), leaving the radii as the only variable parameters to account for the decaying phases of the outburst (right panel, 2nd and 4th plots). Since September 2006 the hottest BB is not anymore needed to fit the spectra (upper limit of $\sim 5\times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$). In this scenario, the already mentioned flattening of the pulsed fraction might be eas-

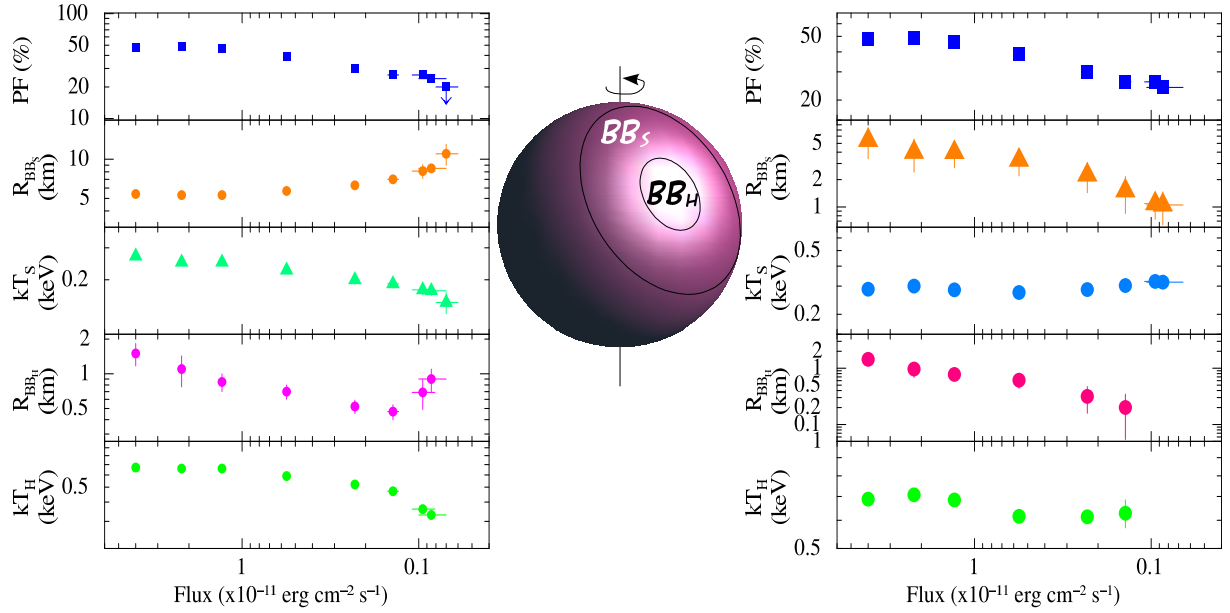


FIGURE 1. Evolution of the spectral parameters for the 2BB (left panel) and 3BB (right panel) models together with the pulsed fraction as a function of the observed 1-10 keV band flux. Central Panel: schematic view of the assumed scenario with marked the emission regions of the hottest BB components.

ily accounted for by the disappearance of the hot BB. A pulse phase spectroscopic analysis do not show any phase lag between the two highest temperature BBs [21].

Further components: During the first two XMM observations (2003-2004) the spectral fit residuals clearly suggest (at a 3.2σ confidence level) the likely presence of an additional hard component above 7–8 keV which we are not able to characterize due to poor statistics in this band. We can only speculate that might be somewhat related to the presence of a hard power-law-like component detected in other AXPs [24, 25] by INTEGRAL and which extends up to (at least) 200 keV [26];

X-ray and radio campaigns: The simultaneous radio and X-ray observations of XTEJ1810-197 carried out in September 2006 and March 2007 showed that the pulse alignment between the two bands is high and stable (see Figure 2), while the pulse width is relatively small (~ 0.1 in phase) in the radio, though not unusual among radio pulsars [27, 28]. This suggests that the X-ray and radio emitting regions are likely different but nearby (or superimposed), the X-rays likely coming from a larger area. Moreover, during the first campaign large radio flux ($\sim 50\%$) and pulse shape variations have been detected which do not correlate with any change (at a few percent level) of the X-ray timing and/or spectral parameters. This suggests that the X-ray emission likely originates deep in the crust and, more in general, the radio and X-ray mechanisms appear different.

We emphasize that the spectral model used above

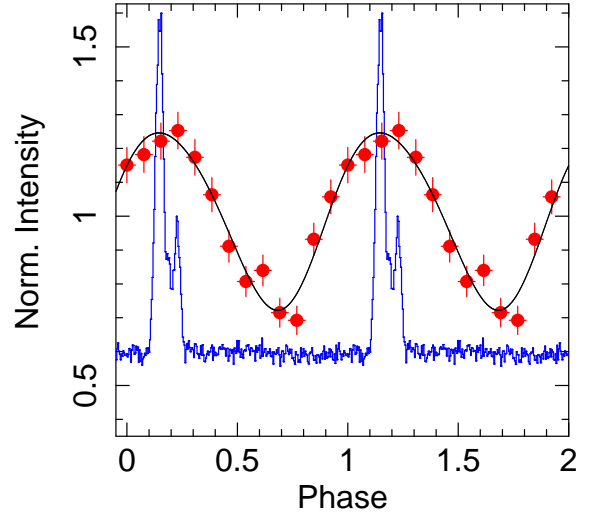


FIGURE 2. XTEJ1810-197 *XMM-Newton* PN+MOS 0.5-10 keV and Parkes 20cm light curves, folded to the spin period, carried out during the September 2006 campaign. Superimposed to the X-ray folded light curve is the best sinusoidal fit [adapted from 27].

(three BBs) is a first attempt to infer the evolution of a number of physical quantities while making use of well assessed and reliable components. The three BB model has the advantage of being model-independent, and of minimizing the number of variable parameters during

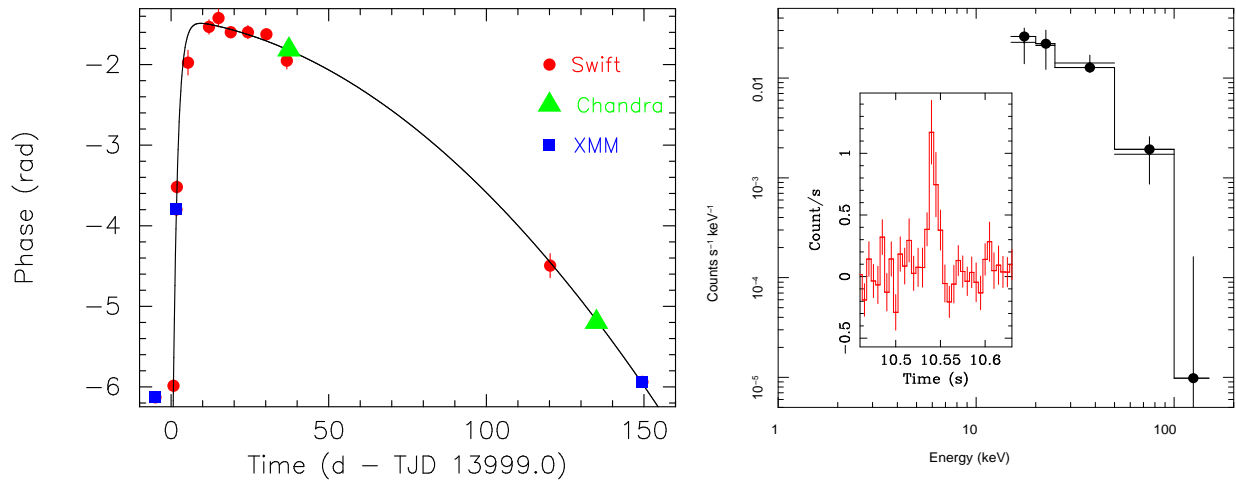


FIGURE 3. Left Panel: phases of the *Swift* XRT, *XMM-Newton* and *Chandra* observations of CXOU J164710.2–455216: a large and quick decaying component is clearly present. Note that the first *XMM-Newton* point (at day -5) would be at the reported phase only in the hypothesis that the pre- and post-glitch parameters are similar [for more details see 14]. Right Panel: the 15-150 keV *Swift* BAT spectrum of the 20ms long burst detected from CXOU J164710.2–455216 on 21st September 2006, together with the 5ms-binned BAT lightcurve in the time interval around the trigger (inset).

the outburst (only the radii are changing and both decreasing). With respect to other model recently developed [see for example 29] we carried out a cross check with the timing properties and rejected all those models/components not able to reproduce the pulsed fraction evolution. All the above inferred information are important in the effort we are currently making in developing and using more detailed and complex (but necessarily model-dependent) modelizations. In particular, the simultaneous fit of the spectra and energy resolved folded light curves might provide a tool to infer the geometry of the surface temperature distribution and to independently check the goodness of the assumed spectral model(s). Finally, we note that the three BB model fit implies that the BB component accounting for the emission from the whole surface is almost unpulsed (pulsed fraction of $9\% \pm 2\%$); this prediction can be easily checked once the source will return into the quiescent state.

CXOU J164710.2–455216: FROM QUIESCENCE TO OUTBURST

On 2006 September 21, the candidate AXP CXOU J164710.2–455216 emitted an intense ($\sim 10^{39} \text{ erg s}^{-1}$) and short (20ms) burst promptly detected by the *Swift* BAT. Together with the burst, large changes in the timing and spectral properties of the persistent component were detected and seen evolving during the subsequent weeks. In particular, the *Swift* XRT monitoring (plus two proprietary *XMM-Newton* and two archival *Chandra* observations) during the first six months since the outburst

allowed to infer the following characteristics:

The BAT burst: The prompt event recorded by *Swift* BAT has an exponential time decay τ of $3.3 \pm 1.0 \text{ ms}$ (1σ confidence level) and the spectrum can be fitted with both a blackbody with kT of $9.9 \pm_{2.2}^{2.8} \text{ keV}$ and a Γ of 1.8 ± 0.5 (see Figure 3, right panel). In both cases a fluence of $\approx 10^{-8} \text{ erg cm}^{-2}$ corresponding to a total energy of $\sim 2 \times 10^{37} \text{ ergs}$ (for a fiducial distance of 5kpc). Compared with the properties of the previously detected AXP bursts, the current burst has a duration within 1σ from the log-normal distribution average value inferred for 1E 2259+586, while the fluence is significantly (a factor of about 50) larger than the mean [10]. There is only one burst, out of ~ 80 detected from 1E 2259+586, with duration and fluence comparable with that of CXOU J164710.2–455216, while a total of three bursts (over the whole burst duration distribution) have fluence comparable or slightly larger than that of BAT.

The phase-coherent timing and the glitch: The pulse phase evolution is consistent with the occurrence of a large glitch ($\Delta\nu/\nu \sim 10^{-4}$), the largest ever detected from a neutron star¹. We also detected a quadratic component in the pulse phases corresponding to a $\dot{P} = 9.2(4) \times 10^{-13} \text{ s s}^{-1}$ and implying a magnetic field strength of 10^{14} G (see Figure 3, left panel). The first 1-

¹ The glitch detection was obtained by minimizing the number of variable peaks in the pulse profile. A less significant timing solution is feasible and requesting only a \dot{P} component. We consider the latter unlikely since it would imply high variability for all the peaks; see [19] for details.

10 keV *Swift* XRT spectrum was carried out ~ 13 hours after the burst detection and showed, in addition to a $kT \sim 0.65$ keV blackbody ($R_{BB} \sim 1.5$ km), a $\Gamma \sim 2.3$ power-law component accounting for about 50% of the observed flux (alternatively, two blackbodies with $kT_s = 0.50 \pm 0.05$ keV with $R_{BBs} = 3.2 \pm 0.4$ km, and $kT_h = 1.1 \pm_{0.1}^{0.2}$ keV with $R_{BBh} = 0.5 \pm 0.1$ km; all the uncertainties are at the 90% level);

The flux and pulsed fraction evolution: The flux decay of CXOU J164710.2–455216 is well described by the function $F \propto t^\alpha$, with index α of -0.28 ± 0.05 (similar to the case of the 2002 1E 2259+586 burst-active phase). Moreover, we found that the PL component decays more rapidly (index α of -0.38 ± 0.11 ; 90% uncertainty) than the BB flux (index α of -0.14 ± 0.10). The pulsed fraction of the 10.61 s pulsations was seen to drop from a value of $\sim 80\%$ (as recorded by an *XMM-Newton* observation few days before the burst) to $\sim 10\%$ few hours after the BAT event. The spectral and timing analysis clearly show that only the blackbody component is responsible for the pulsed flux. In particular, the signal fractional rms as a function of time is well fitted by a power-law with index α of $+0.38 \pm 0.11$, equal (but with opposite sign) to the power-law component decay.

The quiescent properties: Archival *Chandra* data analysis revealed that the modulation in quiescence is 100% pulsed at energies above ~ 4 keV and consistent with the (unusually small-sized) blackbody component being occulted by the neutron star as it rotates.

Radio observations: Since the onset of the outburst, CXOU J164710.2–455216 has been routinely observed in the radio band from Parkes. No pulsed radio emission has been detected so far with an upper limit of $0.04 mJy$ at 1400 MHz [30].

All these results confirmed unambiguously that CXOU J164710.2–455216 is a transient and bursting AXP, showing an unusually high pulsed fraction level in quiescence. In particular, the comparison of the cumulative properties of CXOU J164710.2–455216 with those of other AXPs which showed a similar behavior in the latest years confirmed that these outbursting events are more common than previously thought. The way and timescales with which the post-burst/glitch timing and spectral properties will recover to those in quiescence hold a great potentiality of better understanding the mechanisms which rule the outbursts of AXPs. In particular, the comparison with the XTE J1810-197 outburst evolution might help us in understanding whether other parameters play an important role in the observed properties.

Finally, we note that the BAT detection of the bursts from CXOU J164710.2–455216 opens new perspectives for detecting further burst from known AXPs and for identifying new AXPs/SGRs with the *Swift* mission.

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